

Teeny, tiny Dirac neutrino masses: an unorthodox point of view ¹

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Abstract. There are now strong hints suggesting that neutrinos do have a mass after all. If they do have a mass, it would have to be tiny. Why is it so? Is it Dirac or Majorana? Can one build a model in which a teeny, tiny Dirac neutrino mass arises in a natural way? Can one learn something else other than just neutrino masses? What are the extra phenomenological consequences of such a model? These are the questions that I will try to focus on in this talk.

WHY SHOULD ONE BOTHER WITH A TEENY, TINY DIRAC NEUTRINO MASS?

A subtitle to this talk should perhaps go like “A see-saw-like mechanism without a Majorana mass”. Here, I shall try to present arguments as to why it is interesting and worthwhile to study scenarios in which neutrinos possess a mass which is *pure Dirac* in nature. Along the way, I shall try to argue that one should perhaps try to separate the issue of a see-saw like mechanism from that of a Majorana mass. By ‘see-saw-like mechanism’, it is meant that a “tiny” mass arises due to the presence of a very large scale.

The suggestions that neutrinos do indeed possess a mass came from three different sources, all of which involve oscillations of one type of neutrino into another type. They are the SuperKamiokande atmospheric neutrino oscillation, the solar neutrino results, and the LSND result [1]. The present status of these three oscillation experiments is well presented in this workshop. The future confirmation of all three will certainly have a profound impact on the understanding of the origin of neutrino masses. In particular, it is now generally agreed that if there were only three light, active (i.e. electroweak non-singlet) neutrinos, one would not be able to explain all three oscillation

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phenomena. The confirmation of *all three results* would most likely involve the presence of a sterile neutrino.

Whatever the future experiments might indicate, one thing is probably true: If neutrinos do have a mass, it is certainly tiny compared with all known fermion masses. Typically, $m_\nu \leq O(10^{-11})$ (Electroweak Scale). Why is it so small? Is it a Dirac or a Majorana mass? This last question presently has no answer from any known experiment. The nature of the mass will no doubt have very important physical implications. The route to a gauge unification will certainly be very different in the two cases. Whether or not the mass is Dirac or Majorana, there is probably some new physics which is responsible for making it so tiny. What is the scale of this new physics? What are the possible mechanisms which could give rise to the tiny mass? In trying to answer these questions, one cannot help but realize that there is something *very special* about neutrinos (specifically the right-handed ones) which make them different from all other known fermions. Do they carry some special symmetry?

One example of new physics which might be responsible for a small neutrino mass is the ever-popular and beautiful see-saw mechanism of Gell-Mann, Ramond and Slansky [2], in which a Majorana mass arises through a lepton number violating process. Generically, one would have $m_\nu \sim m_{D\nu}^2/\mathcal{M}$, with $m_{D\nu} \propto$ Electroweak Scale, and $\mathcal{M} \sim$ some typical GUT scale. Since one expects $\mathcal{M} \gg m_{D\nu}$, one automatically obtains a tiny *Majorana* neutrino mass. The actual detail of the neutrino mass matrix is however quite involved and usually depends on some kind of ansatz. But that is the same old story with any fermion mass problem anyway. The crucial point is the fact that the very smallness of the neutrino mass comes from the presumed existence of a very large scale \mathcal{M} compared with the electroweak scale. This mechanism has practically become a standard one for generating neutrino mass. Why then does one bother to look for an alternative?

First of all, there is so far *no evidence* that, if neutrinos do have a mass, it should be of a Majorana type. If anything, the present absence of neutrinoless double beta decay might indicate the contrary. (Strictly speaking, what it does is to set an upper limit on a Majorana mass of approximately 0.2 eV, although actually it is a bound on $\sum_i U_{ei}^2 m_i$). Therefore, this question is entirely open. In the meantime, it is appropriate and important to consider scenarios in which neutrinos are pure Dirac. The questions are: How can one construct a tiny *Dirac* mass for the neutrinos? How natural can it be? Can one learn something new? Are there consequences that can be tested?

A MODEL OF TEENY, TINY DIRAC NEUTRINO MASS

The construction of the model reported in this talk was based on two papers [3,4]. There exists several other works [5] on Dirac neutrino masses which are very different from [3,4]. The first one [3] laid the foundation of the model. The second one [4] is a vastly improved and much more detailed version, with new results not reported in [3]. In constructing this model, we followed the following self-imposed requirements:

- 1) The smallness of the Dirac neutrino mass should arise in a more or less natural way.
- 2) The model should have testable phenomenological consequences, other than just merely reproducing the neutrino mass pattern for the oscillation data.
- 3) One should ask oneself if one can learn, from the construction of the model, something more than just neutrino masses. This also means that one should go beyond the neutrino sector to include the charged lepton and the quark sectors as well. This last sentence refers to work in progress and will not be reported here.

Description of the model

Before describing our model, let us briefly mention a few facts. First of all, it is rather easy to obtain a Dirac mass for the neutrino by simply adding a right-handed neutrino to the Standard Model. This right-handed neutrino (one for each generation) is an electroweak singlet and, as a result, can have a gauge-invariant Yukawa coupling: $g_\nu \bar{l}_L \phi \nu_R + h.c.$. The Dirac neutrino mass would then be $m_\nu = g_\nu \langle \phi \rangle$. With $\langle \phi \rangle \sim 173 GeV$, a neutrino mass of $O(1 \text{ eV})$ would require a Yukawa coupling $g_\nu \sim 10^{-11}$. Although there is nothing wrong with it, a coupling of that magnitude is normally considered to be extremely fine-tuned, if it is put in by hand! Could $g_\nu \sim 10^{-11}$ be *dynamical*? Would the limit $g_\nu \rightarrow 0$ lead to some new symmetry? What would it be? This new symmetry would be the one that protects the neutrino mass from being “large”.

In choosing such a symmetry, we followed our self-imposed requirement # 3: One should learn something more from it than just merely providing a symmetry to protect the neutrino mass. First, in order to implement the symmetry protection, one should assume that this new symmetry is particular to the neutrinos, in particular the right-handed ones since left-handed neutrinos are weak interaction partners of standard charged leptons. Therefore, it will be assumed that all fermions other ν_R 's are *singlets* under this new symmetry.

One of the reasons we adhere to our requirement #3 is the wish to work from the bottom up, instead of from the top down. As a result, we would try

to make every increased step in energy as meaningful as possible.

The symmetry chosen in [3,4] is a chiral gauge symmetry. It is $SU(2)_{\nu_R}$, where the subscript ν_R means that *only* ν_R 's carry $SU(2)_{\nu_R}$ quantum numbers. Why $SU(2)_{\nu_R}$? Because it is a chiral gauge $SU(2)$ which has a very important property: For Weyl fermions transforming as doublets under such a group, there exists an argument due to Witten [6] that says, in a nutshell, that, because of the presence of a non-perturbative global anomaly the number of such Weyl doublets has to be *even* in order for the theory to be well-defined. (In the language of quantum field theory, this means that the generating functional should be non-vanishing.) Amusingly enough, a long-forgotten fact about the SM is related to the Witten anomaly. The absence of such anomaly for $SU(2)_L$ require an even number of electroweak doublets per family, which is the case there: one lepton and three quark doublets. (From a historical perspective, one might say that, had this constraint be known in the early seventies, the SM, as we now know it, would have had an extra strong argument in its favor, prior to the SLAC experiment.) In our case, let ν_R transform as doublets under $SU(2)_{\nu_R}$, i.e. we now have $\eta_R = (\nu_R, \tilde{\nu}_R)$. (Cosmological issues concerning $\tilde{\nu}_R$'s are discussed in [4].) The absence of the Witten anomaly then requires the number of η_R 's to be *even*. If furthermore, η_R 's carry some family indices (if a family symmetry exists) then this constraint can have a profound implication on the issue of family replication. Further remarks can be found in [4].

We know that families *do mix*. In consequence, we need some kind of family symmetry. The family symmetry chosen in [3,4] is a gauge symmetry. This choice is pure prejudice: We believe that gauge theories are better choices for a family symmetry because of the fact that they do provide strong constraints on matter representations and because one might want to mimic the vertical symmetry (the electroweak interactions). We choose $SO(N_f)$ as our family gauge group with all fermions transforming as *vector* representations in order to avoid the usual triangle anomaly. Our model is given by the following extension of the SM:

$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \otimes SO(N_f) \otimes SU(2)_{\nu_R} \quad (1)$$

In [3,4], I have discussed the various arguments used to constrain N_f . In this talk, I shall however restrict N_f to be $N_f = 4$. This means that this is a four-family model. Is a 4th generation ruled out by experiment as one often hears? The answer is: Not at all! For instance, the usual question is the following: What about the Z width which tells us that there are only three light neutrinos? This does not apply to the case when the 4th neutrino is more massive than half the Z mass. Why then would it be so heavy when the other three neutrinos are so light? Isn't it unnatural? The answer is NO as we shall see below. Then, what about the 4th generation quarks and charged leptons? There exists a review [7] dealing extensively with this question. A

quick summary of that review is the statement that there is plenty of room for the discovery of the 4th generation, either at the next upgraded collider experiments at the Tevatron, or at the LHC. I shall now turn to the basic results of the model.

Basic Results of the model

I shall describe the results which are based solely on the assumption that only two oscillation results are correct: The solar and atmospheric neutrino oscillation data. I shall mention at the end a possibility in case all three oscillation experiments are confirmed.

In a nutshell, here are the results obtained in [4]. 1) We obtain three light, *near degenerate* neutrinos. 2) The “tiny” masses are obtained *dynamically* at one loop. One will see below the reason for the use of the term “see-saw-like mechanism with Dirac mass”. 3) The masses of the light neutrinos, m_{ν_i} ($i = 1, 2, 3$), and Δm^2 are correlated in an interesting way: a) If the MSW solution is chosen for the solar neutrino problem, the masses can be as large as O(few eV’s) and can provide enough mass for the Hot Dark Matter (HDM); b) If the vacuum solution is chosen instead, the masses are found to be at most ~ 0.1 eV and, as a result, are too small to be relevant to the HDM. 4) There are a number of phenomenological consequences which can be tested: There is *no* neutrinoless double beta decay since the mass is Dirac; There is a possibility of detection of “light” (a couple of hundreds of GeV’s) vector-like fermions; etc... 5) There are a number of possible cosmological consequences: Baryon asymmetry through neutrino genesis with a pure Dirac neutrino mass; Perhaps some of the very heavy vector-like fermions could be the source of Ultra High Energy Cosmic Rays.

In writing down the Lagrangian for our model, we take into account the fact that our point here is to obtain a pure Dirac mass. Therefore, B-L will be assumed. The particle content is listed in the Table and the Lagrangian is given by

$$\begin{aligned} \mathcal{L}_{Lepton}^Y = & g_E \bar{l}_L^\alpha \phi e_{\alpha R} + G_1 \bar{l}_L^\alpha \Omega_\alpha F_R + G_{M_1} \bar{F}_L \phi \mathcal{M}_{1R} + G_{M_2} \bar{F}_L \tilde{\phi} \mathcal{M}_{2R} + G_2 \bar{\mathcal{M}}_{1L} \Omega_\alpha e_R^\alpha + \\ & G_3 \bar{\mathcal{M}}_{2L} \rho_m^\alpha \eta_{\alpha R}^m + M_F \bar{F}_L F_R + M_1 \bar{\mathcal{M}}_{1L} \mathcal{M}_{1R} + M_2 \bar{\mathcal{M}}_{2L} \mathcal{M}_{2R} + h.c. \end{aligned} \quad (2)$$

After integrating out the F , \mathcal{M}_1 , and \mathcal{M}_2 fields, the relevant part of the effective Lagrangian below $M_{F,1,2}$ reads

$$\begin{aligned} \mathcal{L}_{Lepton}^{Y,eff} = & g_E \bar{l}_L^\alpha \phi e_{\alpha R} + G_E \bar{l}_L^\alpha (\Omega_\alpha \phi \Omega^\beta) e_{\beta R} + \\ & G_N \bar{l}_L^\alpha (\Omega_\alpha \tilde{\phi} \rho_i^\beta) \eta_{\beta R}^i + H.c., \end{aligned} \quad (3)$$

where

$$G_E = \frac{G_1 G_{M_1} G_2}{M_F M_1}; \quad G_N = \frac{G_1 G_{M_2} G_3}{M_F M_2}. \quad (4)$$

TABLE 1. Particle content and quantum numbers of $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \otimes SO(N_f) \otimes SU(2)_{\nu_R}$

Standard Fermions	$q_L = (3, 2, 1/6, N_f, 1)$ $l_L = (1, 2, -1/2, N_f, 1)$ $u_R = (3, 1, 2/3, N_f, 1)$ $d_R = (3, 1, -1/3, N_f, 1)$ $e_R = (1, 1, -1, N_f, 1)$
Right-handed ν 's	Option 1: $\eta_R = (1, 1, 0, N_f, 2)$ Option 2: $\eta_R = (1, 1, 0, N_f, 2);$ $\eta'_R = (1, 1, 0, 1, 2)$
Vector-like Fermions	$F_{L,R} = (1, 2, -1/2, 1, 1)$ $\mathcal{M}_{1L,R} = (1, 1, -1, 1, 1)$ $\mathcal{M}_{2L,R} = (1, 1, 0, 1, 1)$
Scalars	$\Omega^\alpha = (1, 1, 0, N_f, 1)$ $\rho_i^\alpha = (1, 1, 0, N_f, 2)$ $\phi = (1, 2, 1/2, 1, 1)$

As one can see, all neutrinos are *massless* when $SO(4) \otimes SU(2)_{\nu_R}$ is unbroken. Assume $\langle \Omega \rangle = (0, 0, 0, V)$ and $\langle \rho \rangle = (0, 0, 0, V' \otimes s_1)$, the 4th neutrino gets a mass $m_N = \tilde{G}_N \frac{v}{\sqrt{2}}$ with $\tilde{G}_N = G_1 G_{M_2} G_3 \frac{V V'}{M_F M_2}$. One can arrange the masses and couplings in such a way that $\tilde{G}_N \sim O(1)$, and $m_N \sim O(100 \text{ GeV})$. There is nothing unnatural about such a choice. It is *natural* in this scenario to have the 4th neutrino having a mass of $O(100 \text{ GeV})$. One point which is worth emphasizing again is the following: The breaking of $SU(2)_{\nu_R}$ (in addition to $SO(4)$) is essential for m_N to be non-vanishing! At this stage (tree-level), there are *three massless* neutrinos.

It turns out, at one loop, that the three formerly-massless neutrinos acquire a common mass, i.e. they are *degenerate*:

$$\frac{m_\nu}{m_N} = \frac{\sin(2\beta)}{32\pi^2} I\left(\frac{M_F}{M_2}, \frac{M_F}{M_G}, \frac{M_F}{M_P}\right) \quad (5)$$

where $M_{F,2,G,P}$ are masses of particles which participate in the loop diagram and where $\tan \beta = V'/V$. This is shown in Fig. 1. Here $I(\frac{M_F}{M_2}, \frac{M_F}{M_G}, \frac{M_F}{M_P})$ is given by

$$I\left(\frac{M_F}{M_2}, \frac{M_F}{M_G}, \frac{M_F}{M_P}\right) = \frac{1}{M_F - M_2} \left\{ \frac{M_F [M_F^2 (M_G^2 \ln(\frac{M_G^2}{M_F^2}) - M_P^2 \ln(\frac{M_P^2}{M_F^2})) + M_G^2 M_P^2 \ln(\frac{M_P^2}{M_G^2})]}{(M_G^2 - M_F^2)(M_P^2 - M_F^2)} - \right. \\ \left. (M_F \leftrightarrow M_2) \right\}. \quad (6)$$

One important remark is in order here. From Eq. (5), one notices that the neutrino mass does not depend explicitly on the value of the masses $M_{F,2,G,P}$ but only on their *ratios*. If one takes M_F as a “base” mass for example, it turns out that one can obtain quite a small mass for the light neutrinos,

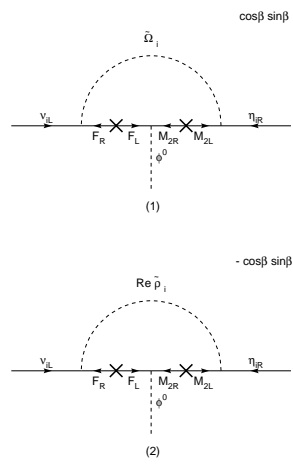


FIGURE 1. Feynman graph showing the computation of \tilde{G}_ν , where $m_\nu = \tilde{G}_\nu \frac{v}{\sqrt{2}}$

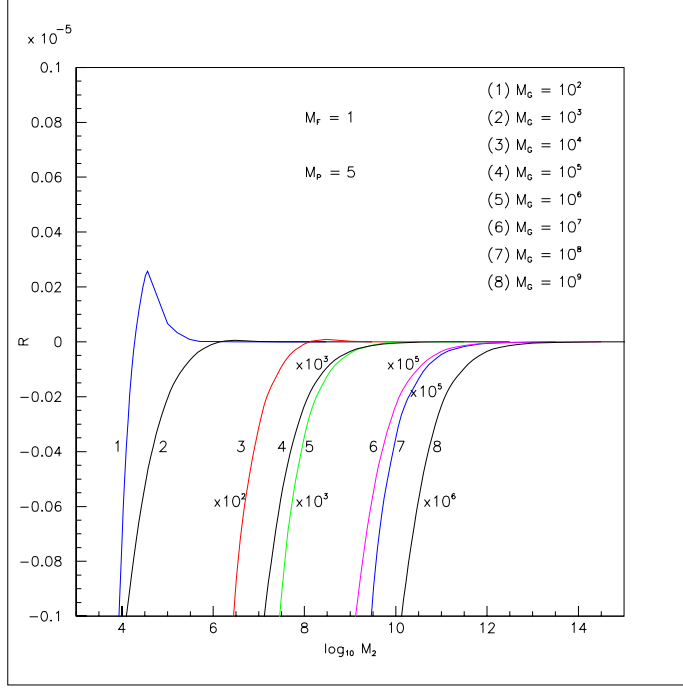


FIGURE 2. The ratio $R \equiv m_\nu/m_N$ (Eq. (23)) as a function of M_2 (in units of M_F , and hence the notation $M_F = 1$), for $M_P = 5$ and for various values of M_G . For visibility purpose, a few curves have been inflated by factors $\times 10^{2,3,5,6}$.

$m_\nu \leq O(10^{-11})m_N$, as long as one has, e.g., $M_2 \gg M_F$, with M_F being an arbitrary number which can be as low as experimentally allowed i.e. $O(200 \text{ GeV})$ [7]. (Remember that F stands for $F = (F^0, F^-)$, where F^0 and F^- are degenerate in mass.) This can be seen from Fig. 2. Just to illustrate this point, a numerical example would be helpful. Take $m_N = 100 \text{ GeV}$, $M_2/M_F = 10^9$, $M_P/M_F = 5$, $M_G/M_F = 10^4$, we obtain $m_\nu = 1.4 \text{ eV}$. I wish to emphasize that this is *not* a prediction. It will have to come from some deeper theory which will fix the above mass ratios and hence m_ν/m_N . This is only meant to illustrate the fact that, in our model, it is quite natural to get a teeny, tiny Dirac neutrino mass. To go further, one needs to lift the degeneracy of the light neutrinos. Before showing how one would go about doing it, let us explain what we meant by “see-saw-like mechanism without a Majorana mass”.

The function I shown in Eq. (6) has the following limit: $I \rightarrow -M_F/M_2$ for $M_2 \gg M_G \gg M_P > M_F$. From Eq. (5), one can see that, in the above limit, $m_\nu \rightarrow \frac{m_N M_F}{M_2} \frac{\sin(2\beta)}{32\pi^2}$. If $M_F \sim O(m_N)$ ($M_F \ll M_2$), one would obtain

$$m_\nu \sim \frac{m_N^2}{M_2} \frac{\sin(2\beta)}{32\pi^2}. \quad (7)$$

This is a typical see-saw-like relation! With a “low” mass (\sim Electroweak scale) vector-like fermion, F , one can qualitatively see that m_ν can be *very small* when $M_2 \gg M_F$. This behaviour is very reminiscent of the see-saw mechanism, except that, in our case, the mass is *Dirac*.

Now the next step is to introduce mixing among the neutrinos in order to lift the mass degeneracy. This can be accomplished, in our model, by involving mixing in the scalar sector. At this stage, the degeneracy among the three light neutrinos is due to a remaining global $SO(3)$ symmetry. This remaining global symmetry can be explicitly broken by the scalar sector as shown in [4]. The offshoot of all this is, in the end, the fact that this explicit breaking depends on a parameter denoted by b in [4]. It turns out that, in a paper under preparation [8], b itself will be severely constrained when our model is extended to the quark sector. This is because the same scalar sector is also involved in the quarks. It is satisfying to see the link between the quark and lepton sectors. This is however not the subject of this talk and I shall now return to the task at hand.

The first case which was investigated in [4] is when the scalar sector is written down in such a way that there is no mixing between the 4th neutrino and the other three in the mass matrix. Something interesting happens here. It turns out that the mass splittings are quasi-degenerate, in the sense that $|m_2^2 - m_1^2| \approx |m_3^2 - m_2^2|$. If this model were to explain both solar and atmospheric oscillation data, this quasi-degeneracy of Δm^2 has to be lifted. Also, the fact that the oscillation data appear to show $\Delta m_{Solar}^2 \ll \Delta m_{Atmospheric}^2$ implies, in the context of our model, that indirectly the data suggests the existence of a 4th neutrino whose mixing with the lighter three will lift the quasi-degeneracy of Δm^2 . Before showing how this could be done, let us see what these results imply. If the vacuum solution for solar neutrinos is preferred, i.e. $\Delta m^2 \sim 10^{-10} eV^2$, then it is found that the median mass value of three almost degenerate neutrinos is $\bar{m}_\nu \lesssim 0.1 eV$. As stated earlier, this is not enough for the HDM scenario. If the MSW solution is preferred, i.e. $\Delta m^2 \sim 10^{-5} eV^2$, the median mass value could be $\bar{m}_\nu \sim O(\text{few } eV's)$, a reasonable value for the HDM scenario.

The fact that $\Delta m_{Solar}^2 \ll \Delta m_{Atmospheric}^2$ indicates, in the context of this model, the existence of more than three light neutrinos. In [4] where only the atmospheric and solar data were taken into account, this means that it indicates the existence of a 4th neutrino. Again through the scalar sector, one can construct e.g. a mixing between the 3rd and 4th neutrino (other possibilities exist). The size of the mixing determines the correct mass splittings. It was found that there are strong constraints on the some of the scalar masses when one requires that $|\Delta m_{12}^2| \sim 10^{-5} eV^2$ and $|\Delta m_{23}^2| \sim 10^{-3} eV^2$.

The next question concerns the oscillation angles. To find out what they

are, one needs to know the leptonic “CKM” matrix: $V_L = U_l^\dagger U_\nu$. In dealing with the neutrino sector of our model, we have presented a case where U_ν can be computed. It is basically given by:

$$U_\nu^{(3)} = \begin{pmatrix} -\frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & 0 \\ \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & 0 \\ 0 & 0 & -1 \end{pmatrix} \quad (8)$$

As for U_l which requires a detailed study of the charged lepton sector, a construction is in progress. In the meantime, just for the purpose of illustration, Reference [9] has been used in which a simple ansatz for the charged lepton sector was given. The reason for using this reference is because it contains an ansatz for U_ν which is similar to ours. Therefore the results should be similar: a small angle MSW solution and a large angle atmospheric solution.

EPILOGUE

I have presented in this talk a model which can “naturally” give rise to a teeny, tiny Dirac neutrino mass, without resorting to the concept of a Majorana mass. What was shown was the need to differentiate between the see-saw mechanism and the existence of a Majorana mass. In this model, the smallness of the light neutrino mass arises in a see-saw-like fashion, with the mass being purely Dirac. As we have argued in the Introduction, the reason for constructing such a model is twofold: a) One does not know experimentally whether the mass is Majorana or Dirac; b) The physics is *very* different in the two cases. At this stage of our knowledge, it is perhaps prudent to explore all different possibilities. Since so much has already been worked out with models using a Majorana mass, any new model which takes a different route should have a clear motivation and predictable consequences. For our model, we have presented clearly our motivation: naturally small Dirac neutrino mass, family replication, etc.; and predictions concerning the neutrino sector: Vacuum solution \nRightarrow HDM, MSW solution \Leftrightarrow HDM, $\Delta m_{Atmospheric}^2 \gg \Delta m_{Solar}^2$ as an indirect indication of a 4th heavy neutrino. Other phenomenological implications include:

1) There is *no* neutrinoless double beta decay because of the fact that we have a Dirac neutrino here.

2) The existence of “long-lived” and “light” (i.e. $\gtrsim 100 GeV$) vector-like leptons (F) whose detection might be possible at the LHC. A study of this kind of search can be found in a comprehensive review [7]. The quark counterparts should also be detectable [8].

3) The existence of several scalars with masses of order TeV’s.

There are several other phenomenological issues to be discussed. For lack of space, a few of those will be briefly mentioned. One is the S parameter for

example. It is well-known that, to leading order, vector-like fermions which carry electroweak $SU(2)_L$ quantum numbers *do not* contribute to S if one has a *degenerate* $SU(2)$ doublet. The reason for this being so is because the right-handed contribution cancels exactly the left-handed contribution. Therefore, to leading order, there is no constraint from the S parameter on the mass of the F -fermions. This point and other issues concerning quarks and leptons beyond the third generation are discussed in [7]. Issues such as the decay of the heavy 4th neutrino can be consulted in [4]. Also, another issue such as the magnitude of flavor-changing neutral currents, e.g. $\mu \rightarrow e\gamma$, will be discussed in an upcoming paper dealing with the charged lepton sector. However, a preliminary statement can be made. For example, in the case of $\mu \rightarrow e\gamma$, there are two kinds of contributions: One coming from the propagation of neutrinos with a non-zero mass inside the loop diagram for the process, and the other one coming from diagrams involving the new vector-like fermions. It turns out that both contributions are negligible: 1) In the first case, it is because $m_\nu \ll M_W$; 2) In the second case, it is because of the cancellations of the type described in [4].

As far as the cosmological implications are concerned, there are:

1) Can the fermion \mathcal{M}_2 be the source of Ultra High Energy Cosmic Rays ($E > 10^{11} GeV$)? For example if $M_F \sim 200 GeV$ then $M_2 \sim 2 \times 10^{11} GeV$? Would the decays of \mathcal{M}_2 (e.g. $\mathcal{M}_{2R} \rightarrow W_L^\pm F^\mp \rightarrow$ high energy quarks and leptons) be responsible for UHECR? This deserves a closer look.

2) The possibility of Baryon Asymmetry from neutrinogenesis. This is a scenario of Ref. [10]. The ingredients needed for such a scenario to work are basically: 1) a tiny, pure Dirac neutrino mass; 2) A decay process from some superheavy particles at the GUT (or similar) scale into right-handed neutrinos such that there is an asymmetry between right-handed neutrinos and anti-neutrinos; 3) a B+L violating process from the electroweak sphaleron. Since the Dirac neutrinos have a tiny Yukawa coupling (which is dynamical in our case), the part of B+L which is stored in the right-handed neutrinos, $(B+L)_R$, survived the sphaleron “washout”. So if one starts out with B-L=0, this process can generate a *net* baryon number, $n_B = n_L \propto n_{\nu_R}$.

Last but not least, a Dirac neutrino mass would certainly imply a different route to unification, different from the popular scenario such as $SO(10)$.

One last remark is in order here. If all three oscillation experiments were to be confirmed in the future, there seems to be a need for a sterile neutrino. How will it fit in our framework? It turns out that some modifications of the previous analysis will be needed but the basic framework is still the same. This work is in progress.

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